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U–Pb and Hf isotope analysis of detrital zircons from Devonian–Permian strata of Kotel'ny Island (New Siberian Islands, Russian Eastern Arctic): Insights into the Middle–Late Paleozoic evolution of the Arctic

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ABSTRACT

U–Pb and Lu–Hf isotope analyses of detrital zircons collected from the Devonian–Permian strata of Kotel'ny Island (New Siberian Islands, Eastern Russian Arctic) provide vital information about provenance areas and history of the poorly studied Paleozoic basement of the Laptev and East Siberian shelves. Based on detrital zircon signatures, our study reveals that the studied succession can be divided into two distinct groups: Devonian–Lower Carboniferous and uppermost Carboniferous–Permian. U–Pb and Lu–Hf isotope signatures of detrital zircons from the Devonian–Lower Carboniferous deposits correspond to well-known Precambrian–Early Paleozoic magmatic and metamorphic events within the northern part of Baltica, indicative of a peri-Baltican affinity of the New Siberian Islands during this time. A lack of zircon ages close to the depositional age of the formation, along with a mature composition of the sandstones, suggest that the Devonian–Lower Carboniferous succession formed as a result of extensive sediment reworking from a distal provenance. By contrast, uppermost Carboniferous–Permian sandstones have an immature composition, with numerous young detrital zircons close to the age of sedimentation and Hf signatures typical of a continental arc environment. We therefore suggest that the provenance for these younger deposits was located within a coeval orogeny and based on previous studies, we conclude that these deposits were sourced from the north-western part of the Uralian Orogen.

1. Introduction

The New Siberian Islands (NSI) archipelago represents an exposed Paleozoic–Mesozoic fragment, located in the eastern part of the Russian Arctic between the Laptev and East Siberian seas. The archipelago comprises three island groups: Anjou, De Long and Lyakhovsky (Fig. 1a,b). The islands were extensively studied 30–40 years ago by the Research Institute of Arctic Geology (Kos'ko et al., 1985), when detailed geological maps were compiled. A number of different tectonic models have been developed to explain the tectonic affinity of the NSI throughout the Paleozoic–Mesozoic. Kuzmichev (2009) suggest that the NSI represent the distal extended north-eastern (in present co-ordinates) part of the Siberian Craton, while Metelkin et al. (2014) supposed it was a discrete terrane separated from the Siberian Craton throughout the Paleozoic. Davydov (2016) proposed that the Chukotka, Wrangel Island and NSI terrane, including Zhokhov Island, was located close to the Sverdrup Basin, Arctic Alaska (Brooks and Lisburne Ranges), Spitsbergen, Franz Josef Land, Barents Shelf and Timan-Pechora, based on comparable fusulinid faunas.

Recent U–Pb studies on the Lower Paleozoic clastics of the De Long Islands suggest a non-Siberian provenance (Ershova et al., 2016a), whilst a pioneering study of the Upper Paleozoic rocks of Kotel'ny Island suggest a Laurentian or Baltican affinity (Ershova et al., 2015b). However, previous provenance studies were based on a very limited number of samples, therefore further studies with a larger sample set are urgently required.

Here we present U–Pb and Hf isotopic studies of detrital zircons from all the stratigraphic units described from the Devonian–Permian succession of Kotel'ny Island (Anjou Island group) containing terrigenous rocks. The aim of this study is to more definitively identify the

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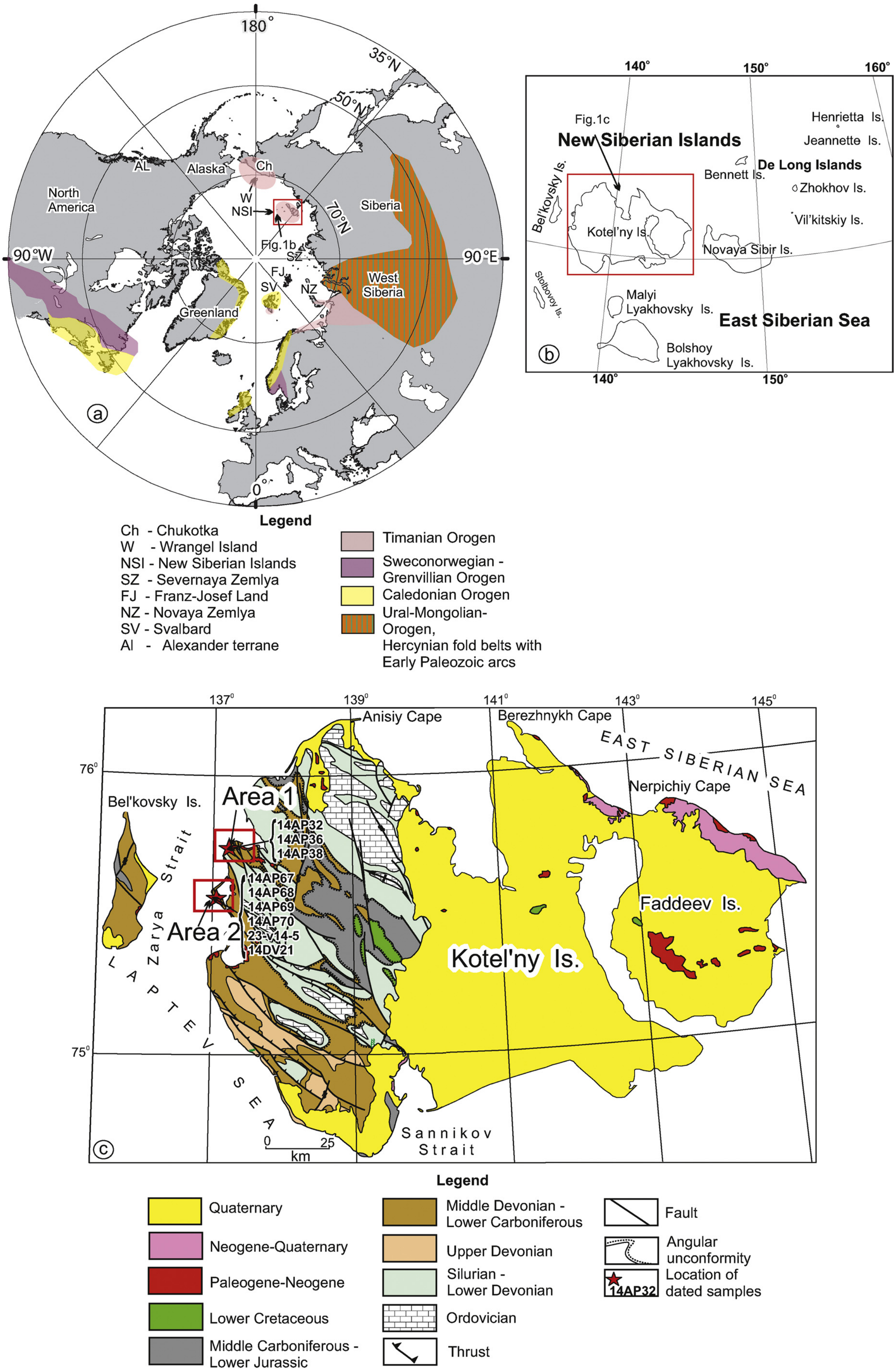

(caption on next page)

Fig. 1. a – Regional setting of the study area depicting the locations discussed in the text and the major orogenic systems; b – Sketch map of NSI; c – Geological map of Kotel'ny Is. with location of study section (modified from Parfenov et al., 2001).

Paleozoic affinity of the NSI, building on the earlier work with limited sample sets, and help to refine Paleozoic paleogeographic and paleotectonic models for the circum-Arctic.

1.1. Geological background

Kotel'ny Island is mainly composed of deformed Paleozoic sedimentary rocks, with locally preserved Mesozoic and Cenozoic rocks within synclines and around the periphery of the island (Kos'ko et al., 1985; Kos'ko and Korago, 2009). The Paleozoic–Mesozoic rocks of Kotel'ny Island are deformed into a series of northwest-striking folds, which are associated with reverse faults and thrusts of south-western and north-eastern vergence (Parfenov et al., 2001). The analysed samples have been collected from two study areas located along the western and north-western coast of Kotel'ny Island (Fig. 1c). Area 1 is located in the north-western part (Fig. 1c), where Middle–Upper Paleozoic carbonates are mainly exposed, with subordinate exposures of uppermost Paleozoic and Triassic clastic rocks. Cenozoic deposits are exposed in a few small outcrops. Area 2 (Fig. 1c) is located in the western part of Kotel'ny Island, where Devonian–Permian strata outcrop along the coast of Tas-Ary Island (Fig. 1c) and are unconformably overlain by Cenozoic strata.

1.1.1. Stratigraphy

The Ordovician–Silurian deposits crop out in the central part of Kotel'ny Island along the banks of rivers. The most complete Devonian–Permian sections are located along the coast of the island. A few scattered exposures are also known in the central part of the island, where they are located within deeply incised river valleys.

The Ordovician–Silurian succession comprises dolomites, limestones and marls, attaining a thickness of up to 1700 m (Kos'ko et al., 1985; Kos'ko and Korago, 2009).

1.1.2. Devonian

The Lochkovian (Pshenitsin Formation) deposits lie conformably on Silurian carbonates and are represented by alternating micritic, bioclastic and clayey limestones, marls and dolomites, with subordinate beds of clay, varying from 200 to 400 m in thickness (Kos'ko et al., 1972; Cherkesova, 1972). We have studied the Lochkovian strata in Area 1, where they are represented by alternating marls, dolomites and limy shales (Fig. 2).

Pragian–Lower Emsian deposits (Basykh-Karga Formation; 165–300 m thick) comprise micritic and bioclastic limestones with subordinate beds of clayey limestones in the north-western part of the island, whilst in the south-eastern part micritic thinly bedded limestones and black shales were deposited (Kos'ko et al., 1985). The Pragian–Lower Emsian deposits have been studied in the north-western part of Kotel'ny Island and are represented by bioclastic limestones with subordinate beds of clayey limestones (Area 1) (Fig. 2).

Uppermost Lower Emsian–Upper Emsian strata (Shlupochnaya Formation) are represented by bioclastic limestones with subordinate beds of black marls in the north-western part of the island, whilst in the south-western part the sediments consist of micritic limestones with beds of shale, reaching an estimated thickness of about 300 m (Kos'ko et al., 1985). The uppermost Lower Emsian–Upper Emsian strata have been observed in the field near Polar station (Area 1) (Fig. 2). They comprise grey to black limestones with rare thin interbeds of limy shales. The maximum thickness observed here reaches 50 m.

The Middle Devonian (Eifelian–Givetian) strata (Sokolov Formation) disconformably lie on Lower Devonian and Silurian deposits in the northern part of the island, and conformably in its southern part (Kos'ko et al., 1985). The strata are up to 600 m thick and are represented by alternating bioclastic and micritic limestones, with thick beds of carbonate breccias comprising angular clasts of up to pebble and boulder size (up to 5 m in diameter). The Eifelian–Givetian deposits have been studied in Area 1, where they crop out in several exposures varying significantly in size and stratigraphic completeness. They are mostly represented by carbonate breccias. Units of layered micritic limestones with thickness reaching a few tens of meters also occur within the succession (Fig. 2).

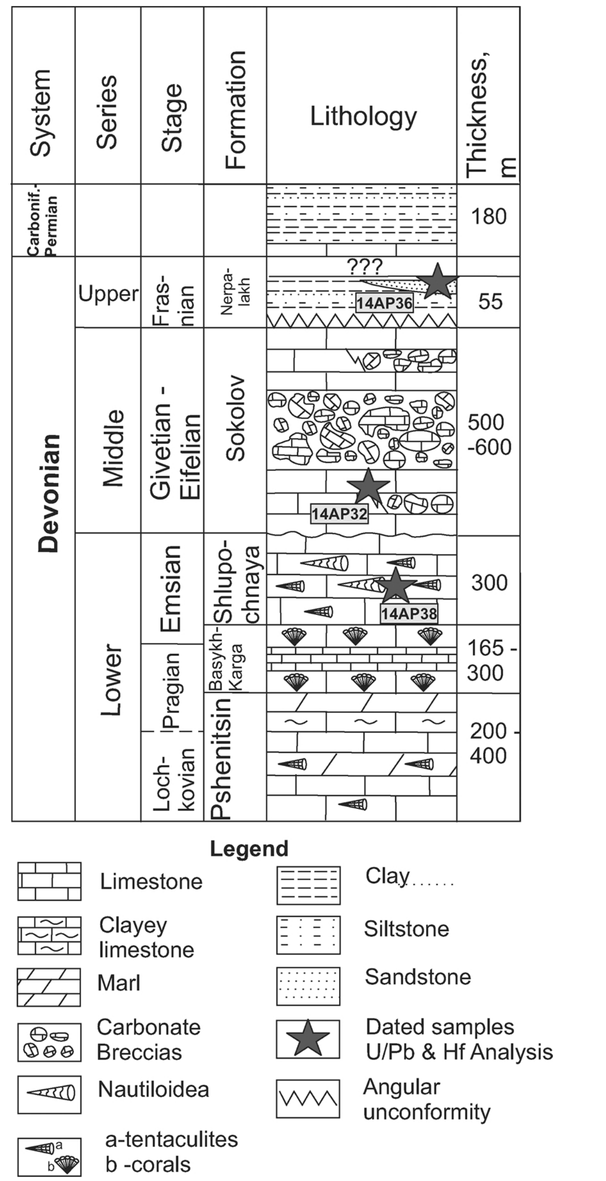

Fig. 2. Stratigraphic column of Devonian-Permian rocks of study Area 1 (thickness and lithology are mainly based on our field data with age constrains mainly based on Kos'ko et al., 1985).

The Frasnian deposits (Nerpalakh Formation) are separated from Middle Devonian carbonates by an angular unconformity (Prokopiev et al., 2015) and comprise 50 m of alternating varicolored green and red clays and siltstones, with subordinate beds of marls, bioclastic limestones and sandstones in the north-western part of the island. In the south-western part of the island, Frasnian deposits comprise alternating greyish clays and siltstones, with subordinate layers of sandstone and limestone. Kos'ko et al. (1985) suggest that the thickness of Frasnian

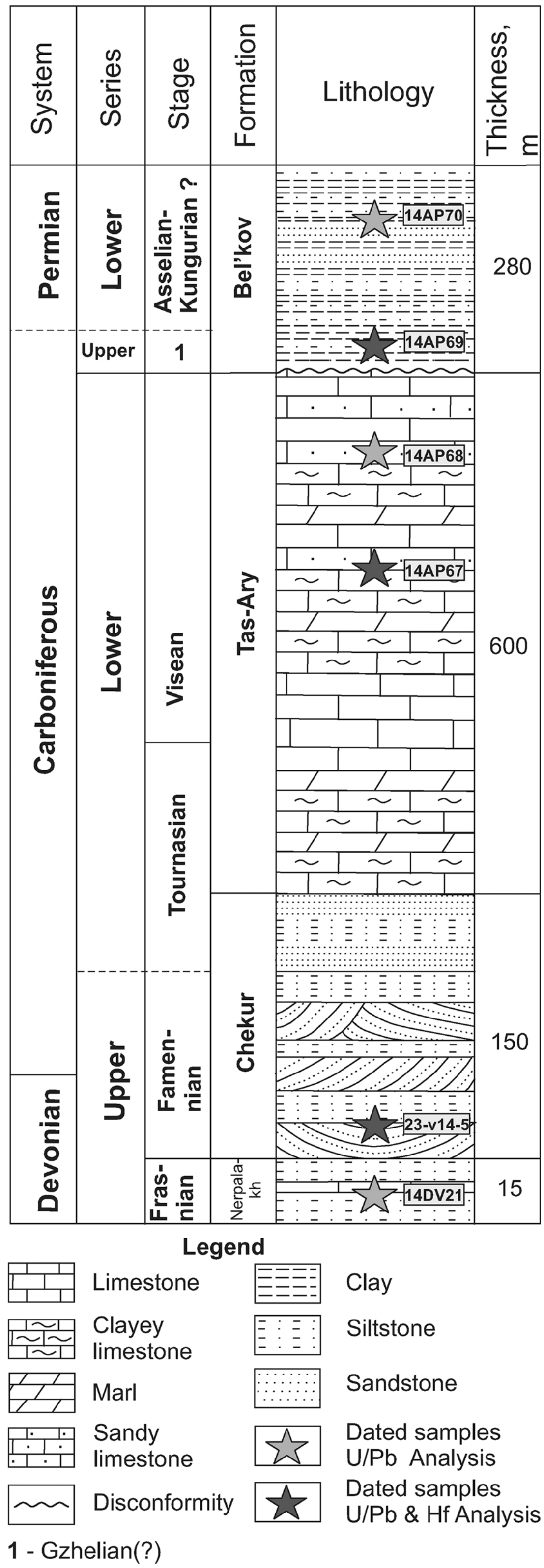

Fig. 3. Stratigraphic column of Devonian-Permian rocks of study Area 2. (thickness and lithology are mainly based on our field data with age constrains mainly based on Kos'ko et al., 1985).

deposits in the southern part of the island varies from 1 to 7.7 km, however this great thickness is likely to be an overestimation due to repetition of the stratigraphy by faulting and folding (Ershova et al., 2016b). The Frasnian deposits crop out in both study areas. The 50 m-thick alternating red and greenish grey siltstones, with subordinate beds of marls and limestones, have been observed in Area 1, ~1 km to the south of the Sokolov River mouth (Fig. 2). The Frasnian succession of Area 2 comprises greenish grey siltstones with beds of silty sandstones and shales. The estimated thickness here does not exceed a few tens of meters (Fig. 3).

Famennian–Lower Tournaisian deposits (Chekur Formation) comprise 150–1000 m of alternating varicolored sandstones and siltstones, with rare beds of argillites, conglomerates and limestones (Kos'ko et al., 1985). The Famennian–Lower Tournaisian strata have been studied along the western coast of Tas-Ary Island (Area 2). Here, several hundred meters of alternating sandstones and siltstones with subordinate beds of argillites are exposed (Fig. 3). As these rocks are unfossiliferous, the age of these deposits has been crudely estimated based on the presence of Frasnian rocks below and Visean strata above.

1.1.3. Carboniferous

The Tas-Ary Formation is exposed along the coast of Kotel'ny Island and represented by up to 1100 m of bioclastic, micritic and clayey limestones, with subordinate beds of shale. It was Kos'ko et al. (1985) dated the formation as Upper Tournaisian–Serpukhovian. Lower Carboniferous deposits have also been described from scattered outcrops in the central part of the island, and are represented by 300–400 m of clayey and bioclastic limestones and shales (Kos'ko et al., 1985). Tas-Ary Formation strata exposed along the western part of Tas-Ary Island (Area 2) comprise silty marls and marls at the base, limestones with a 40 m thick unit of shales in the middle part, and alternating shales, marls and limestones in the upper part of the succession. Our brachiopod findings suggest an Upper Tournaisian–Visean age for the Tas-Ary Formation across Area 2 (Baranov V.V. pers. comm.), with a total thickness of ~500–600 m (Fig. 3).

Overlying strata of the Bel'kov Formation are typically 400–450 m thick and are locally exposed in the western and south-western parts of the island, comprising siltstones, shales, and sandstones with subordinate beds of conglomerate, breccia and limestone (Area 2) (Kos'ko et al., 1985). In the north-western and central parts of Kotel'ny Island, strata are up to 30 m thick and represented by limestones and carbonate breccias, with subordinate beds of sandstones and siltstones. Bel'kov Formation strata exposed along the western part of Tas-Ary Island (Area 2) comprises shales and siltstones with subordinate beds of sandstones, attaining a total thickness of up to 180 m. However, whilst Kos'ko et al. (1985) previously suggested a Bashkirian age for the Bel'kov Formation, our study reveals a younger cluster of detrital zircon ages as young as latest Carboniferous–Early Permian, suggesting a younger age for the formation.

1.1.4. Permian

The Permian deposits of north-western Kotel'ny Island comprise shales with subordinate beds of siltstone and a few beds of limestone. Based on brachiopod biostratigraphy, the Lower Permian strata are up to 80 m thick, whilst Upper Permian strata are up to 100 m thick (Kos'ko et al., 1985). The Permian strata of Area 1 crop out along the coast of the Laptev Sea and in a few small exposures along the banks of small creeks inland (Fig. 2). They comprise siltstones and shales with subordinate beds of silty sandstones. The total thickness here does not exceed a few hundred meters. As described above, the Bel'kov Formation crops out in the southern margin of Tas-Ary Island (Area 2) and based on this study, is latest Carboniferous–Early Permian in age (Fig. 3).

2. Methods

Samples were crushed and heavy minerals were concentrated using standard techniques at the Institute of Precambrian Geology RAS (St. Petersburg). The zircon grains were mounted in epoxy and polished.

Samples 14AP70 and 14DV21 were analysed at the Geological

Survey of Denmark and Greenland (Copenhagen), using the laser ablation – single collector – magnetic sector-field – inductively coupled plasma – mass spectrometry (LA-SF-ICP-MS) method, employing a Thermo-Fisher Element 2 mass spectrometer coupled to a New Wave UP213 laser ablation system. Data were acquired by single spot analyses using a frequency of 10 Hz, 3–10 J/cm^2 and a spot diameter of 25 or 30 μm, producing a crater depth of ca. 20–25 μm. The methods employed for analysis and data processing are described in detail by Gerdes and Zeh (2006) and Frei and Gerdes (2009).

Samples 24-v14-5, 14AP36, 14AP32, 14AP38, 14AP69, 14AP67 were analysed at the Department of Geosciences, University of Oslo. U–Pb and Lu–Hf analyses were carried out by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), using a Nu Plasma HR multicollector mass spectrometer equipped with a New Wave LUV 213 Nd-YAG laser microprobe. Additional information about the U–Pb analyses is given in the analytical protocols of Andersen et al. (2009) and Rosa et al. (2009), whereas those of Elburg et al. (2013) were followed for Lu–Hf measurements. $^{207}Pb/^{206}Pb$ ages are reported for > 1.0 Ga grains, and $^{206}Pb/^{238}U$ ages reported for ≤ 1.0 Ga grains. Following Gehrels (2012), analyses with greater than 30 positive and 10 negative discordance were excluded from the results. The Lu–Hf study was conducted on zircons with less than 10% discordance and 10% reverse discordance. All U–Pb diagrams have been plotted using Isoplot 4 software. Peaks have been identified by the AgePick program. Data tables are provided in Attachment 1a, b and Attachment 2 in Supplementary materials.

3. Results of U–Pb analyses

3.1. Area 1

Sample **14AP38** was collected from the uppermost Lower Emsian–Upper Emsian strata (Shlupochnaya Formation) (Fig. 2). The Shlupochnaya Formation mainly comprises carbonates, however this sample has been collected from a tempestite layer where thin lenses of sandstone occur. The sandstone is a fine- to medium-grained quartz arenite (Fig. 4-1).

Precambrian grains comprise 89% of the total population, with a single Archean grain yielding an age of 2569 ± 11 Ma (Fig. 5). Paleoproterozoic zircons form a prominent peak at ca. 1617 Ma, while Neoproterozoic and Paleoproterozoic grains prevail within the Precambrian zircons, comprising 26% and 44% respectively of the total population. Mesoproterozoic grains form prominent peaks at ca. 1544, 1483, 1393, 1344, 1281, 1159, and 1079 Ma. Early Neoproterozoic grains form peaks at ca. 981, 952 and 828 Ma, however Late Neoproterozoic grains prevail with prominent peaks at 736, 650, 601, 561 and 546 Ma. Early Paleozoic grains contribute 11% of the population and form peaks at 485 and 444 Ma.

Sample **14AP32** originated from Middle Devonian (Eifelian–Givetian) strata (Sokolov Formation) (Fig. 2). Sandstone has been collected from tempestite beds, where clastics occur as thin lenses in hummocky cross-stratified units. The dated sandstone is a quartz arenite. The three Archean grains do not form a prominent peak, while Paleoproterozoic grains comprise 28% of the population and are grouped into numerous peaks at 1937, 1859, 1829, 1789, 1733 and 1643 Ma. Mesoproterozoic zircons comprise 19% of the total population and peak at 1422, 1209, and 1100 Ma. Neoproterozoic grains (31%) prevail within the Precambrian zircons and can be divided into two distinct populations: Early Neoproterozoic with peaks around 1000, 961, 944, 915, and 833, and Late Neoproterozoic grouped at 646, 630, 613, 586, and 557 Ma. Paleozoic grains contribute 19% of the population and form peaks at 493 and 488 Ma (Fig. 5).

Sample **14AP36** comprises fine-grained silty quartz arenite and was collected from Frasnian deposits (Nerpalakh Formation) (Fig. 2). Ninety two percent of the dated grains are Precambrian in age, with a single Archean grain yielding an age of 2654 ± 10 Ma. Paleoproterozoic grains contribute 26% of the total population and form major peaks at 1753, 1714, and 1616 Ma. Mesoproterozoic grains comprise 32% and form major peaks at 1553, 1365, 1264, and 1157 Ma, with smaller peaks at 1505 and 1479 Ma. Neoproterozoic grains contribute 31% of the population and form peaks at 972, 948, 743, 670, 628, 598, 585, and 568 Ma (Fig. 5). Early to Middle Paleozoic grains comprise 8% of the population and do not form distinct peaks.

3.2. Area 2

Sample **14DV21** was collected from Frasnian deposits (Nerpalakh Formation) (Fig. 3). It consists of fine-grained clayey quartz arenite (Fig. 4-2.). The three Archean grains do not form a prominent peak, whilst Paleoproterozoic grains comprise 27% of the population and are grouped into several peaks around 1929, 1826, 1865, 1750, 1719, 1660, and 1636 Ma. Mesoproterozoic grains prevail within the Precambrian zircons and contribute 33% of the population, grouping at 1531, 1327, 1299, 1257, and 1161 Ma. Neoproterozoic grains comprise 27% and form two populations at 658 and 546 Ma (Fig. 6). The Paleozoic grains are grouped at 467 Ma.

Sample **24-v14-5** was collected from Famennian–Lower Tournaisian sandstones of the Chekur Formation (Fig. 3) and comprises a quartz arenite (Fig. 4-3). Paleoproterozoic zircons comprise 9% of the total population and are grouped at 1644 Ma. Thirty one percent of the dated zircons are of Mesoproterozoic age and form multiple peaks between 1600 and 1485 and 1310–1170 Ma. Neoproterozoic grains comprise 43% of the population and group at 987, 899, 680, 649, 616, and 553 Ma. Seventeen percent of the dated zircons are of Paleozoic age, of which 9% are Cambrian and grouped at 533 and 528 Ma. Ordovician and Silurian grains are grouped in three small peaks at 456, 489, and 427 Ma (Fig. 6).

Sample **14AP67** was collected from the middle part of the Upper Tournaisian–Visean Tas-Ary Formation (Fig. 3), consisting of fine- to medium-grained quartz arenite. Sixteen percent of the dated grains are Paleoproterozoic in age, grouping in a peak at 1645 Ma. Mesoproterozoic grains comprise 16% of the population and group around 1448 and 1150 Ma. Neoproterozoic grains (32% of the population) prevail within the Precambrian zircons and form multiple peaks between 950 and 850 and 660–560 Ma. Early Paleozoic zircons (25% of the population) form peaks at 536, 500, 468, 436, and 422 Ma (Fig. 6).

Sample **14AP68** was collected from the upper part of the Upper Tournaisian–Visean Tas-Ary Formation (Fig. 3) and consist of quartz arenite (Fig. 4-4). The majority of the dated grains are Precambrian in age, with Archean grains comprising 4% of the population and forming a peak at 2674 Ma. Paleoproterozoic zircons comprise 20% of the total population and are grouped at 1728, 1657, and 1621 Ma. Thirty four percent of the dated zircons are of Mesoproterozoic age and form multiple peaks between 1590 and 1300 Ma. Neoproterozoic grains comprise 22% of the population and group at 971, 689, 636, 612, 539, and 547 Ma. Paleozoic grains contribute 26% of the total population, whilst Early Paleozoic grains comprise 21%, forming peaks at 547, 539, 528, 512, and 428 Ma (Fig. 6).

Sample 14AP69 originated from Upper Carboniferous–Lower Permian strata of the Bel'kov Formation (Fig. 3). The sample consists of fine-medium-grained lithic sandstone containing numerous volcanic grains (Fig. 4-5), and has been dated as Bashkirian in age by Kos'ko et al. (1985). However, the youngest cluster of detrital zircons is dated as 302 Ma, suggesting a latest Carboniferous or younger age. Precambrian grains contribute 18% of the population and form peaks at 1848 and 638 Ma. Paleozoic grains comprise 82% of the population with Early Paleozoic zircons forming peaks at 488, 458, and 444 Ma, while Middle–Late Paleozoic zircons form peaks at 328, 356, 384, and 302 Ma (Fig. 6).

Sample **14AP70** was also collected from the Bel'kov Formation, however further upsection from **14AP69** (Fig. 3), and comprises fine-grained lithic arenite containing numerous volcanic grains (Fig. 4-6).

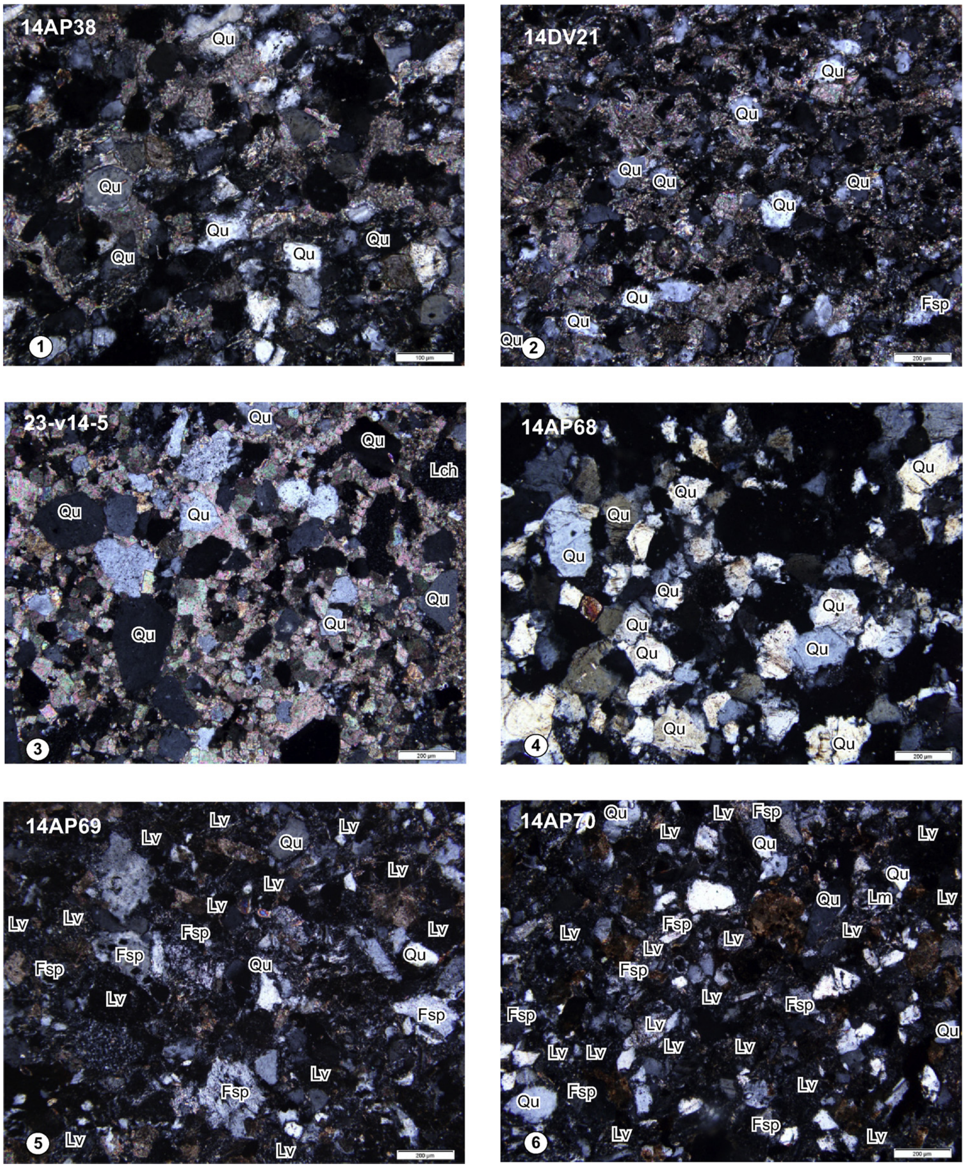

Fig. 4. Selected images of dated samples: 1. 14AP38–fine- to medium grained quartz arenite from Uppermost Lower Emsian – Upper Emsian strata (Shlupochnaya Fm.); 2. 14DV21–quartz arenite from Frasnian strata (Nerpalakh Fm.); 3. 23-v14-5–quartz arenite from the Famennian-Lower Tournaisian (Chekur Fm); 4. 14AP68–fine- to medium grained quartz arenite of the Upper Tournaisian – Visean Tas-Ary Fm; 5. 14AP69–fine-medium grained lithic sandstone from the Upper Carboniferous – Lower Permian strata (Bel'kov Fm); 6. 14AP70–fine-medium grained lithic sandstone from the Upper Carboniferous – Lower Permian strata (Bel'kov Fm). Abbreviation: Qu – qurtz, Fsp – feldspar; Lv – volcanic grains; Lch – chert grains; Lm – metamorphic grains.

The youngest cluster of detrital zircons are dated as 283 Ma, suggesting an Early Permian age. The majority of dated grains are Paleozoic in age (76%), with Precambrian zircons comprising 24% of the population and grouping in peaks at 802, 786, and 768 Ma. Early Paleozoic grains form peaks at 522, 505, 493, 483, and 461 Ma. Middle–Late Paleozoic zircons prevail within the dated grains, forming peaks at 391, 359, 305, 297, and 283 Ma (Fig. 6).

4. Results of Lu–Hf isotopes of detrital zircon

Five samples of Early Devonian–latest Carboniferous (Early Permian?) age were analysed for Lu–Hf isotopes, including: **14AP36, 14AP38, 23-v14-5, 14AP67** and **14AP69** (Fig. 7). In total, 209 grains were analysed. Devonian to Lower Carboniferous samples (**14AP36, 14AP38, 23-v14-5, 14AP67**) show similar εHf(t) signatures. Paleoproterozoic and Mesoproterozoic zircon εHf(t) values are mainly positive or only slightly negative, varying from −10 to +10, although a few grains have an extremely negative εHf(t) of up to −27. The Early Neoproterozoic (1000–800 Ma) zircon population forms a strong vertical array with εHf(t) values falling in a range between −15 to +5. The Late Neoproterozoic–Cambrian grains show a vertical array of εHf (t) mainly falling in the range from −10 to +10. Ordovician–Devonian zircons mostly have negative εHf(t) values ranging from to 0 to −10, with a few grains with positive εHf(t) values (Fig. 7).

The **14AP69** sample has detrital zircon and εHf(t) signatures that are different from the other samples. Thus, seven Paleoproterozoic grains have εHf(t) values ranging from +4 to − 8. The Late Neoproterozoic–Cambrian cluster of detrital zircons has εHf(t) values ranging from +5 to −12, while Ordovician–Devonian grains mostly have positive values between +2 and +9. The predominant Carboniferous–Permian population of detrital zircons forms a strong vertical array on the εHf(t) vs. age plot, with εHf(t) values falling in a range between −10 and +8 (Fig. 7).

5. Discussion

Our detrital zircon results from the Devonian–Permian sandstones of Kotel'ny Island provide new geologic constraints on the Middle–Late Paleozoic paleogeography and tectonics of the Eastern Russian Arctic. Clastic provenances are determined by comparing data obtained from this study with those of previous detrital zircon studies of coeval strata across the Arctic realm. The distribution of detrital zircon ages is quite similar within Devonian–Lower Carboniferous deposits, while sandstones of the Bel'kov Formation (Upper Carboniferous– Lower Permian)

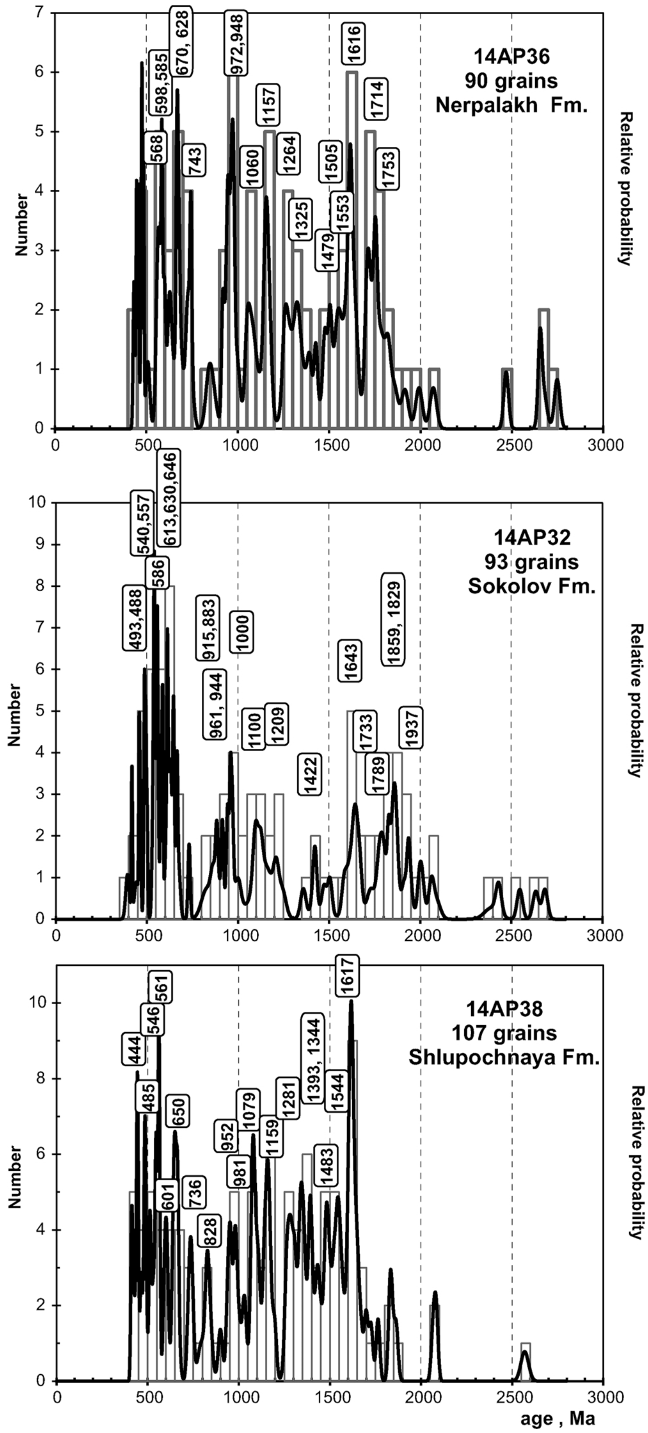

Fig. 5. Probability density diagram and superimposed histogram of U-Pb detrital zircon ages from Devonian rocks of Area 1.

are quite different, suggestive of a switch in the provenance. A shift from mainly quartz arenite (mature sandstones) within the Devonian–Visean strata, to lithic (immature) sandstones within the uppermost Carboniferous–Permian strata, also support a changing provenance.

5.1. Devonian–lower carboniferous clastics

The majority of dated zircons within the Devonian–Lower Carboniferous clastics lie between 1800 and 900 Ma, ages which have not been reported from magmatic rocks comprising the basement of the Siberian Craton (Smelov and Timofeev, 2007). The Siberian Craton basement comprises Archean blocks (2.5–2.6 Ga) reworked and accreted to each other at 1850–1950 Ma (Rozen, 2003; Smelov and Timofeev, 2007). Furthermore, latest Paleoproterozoic–Mesoproterozoic magmatic rocks have a very limited distribution within the basement of the Siberian Craton, leading to introduction of the term “Siberian magmatic gap” between 1800 and 900 Ma by Gladkochub et al. (2010). A significant amount of Mesoproterozoic aged grains within zircon populations from Lower Carboniferous clastics of Siberia have also not been reported from U–Pb provenance studies (Ershova et al., 2015a, 2013; Prokopiev et al., 2013). Previous U–Pb detrital zircon provenance studies of Paleozoic strata of Kotel’ny Island (Ershova et al., 2015b), based on a smaller dataset, tentatively proposed a Laurentian or Baltican affinity of the area. The significantly larger data set of this study, along with the addition of Hf signatures, allows us to construct a much more robust interpretation of provenance areas and therefore affinity of the NSI. The latest Paleoproterozoic–Mesoproterozoic zircon ages are generally in good agreement with zircon ages known from both the Laurentia and Baltica paleocontinents, specifically in relation to magmatic and metamorphic events associated with the Grenvillian-Sveconorwegian orogenies (Bingen et al., 2008; McLelland et al., 2010; Rivers, 2008). However, the Precambrian history of Laurentia is characterized by the so called North American Magmatic Gap (NAMG) (1610–1490 Ma), with no big magmatic or metamorphic events known of this age (Ross and Villeneuve, 2003; van Schmus et al., 1993). Our study reveals that there is an abundance of zircons falling in the age range of the NAMG within the Devonian–Visean strata of Kotel’ny Island, therefore we conclude that Laurentia is unlikely to be the primary provenance for the Devonian–Lower Carboniferous clastics.

Zircon ages of ca. 1950–1800 Ma, reported from the Devonian–Lower Carboniferous samples, could be correlated with magmatic events within the Svecofennian Orogen, with rocks of these ages described from the northern part of the East European Platform (Baltica paleocontinent) (Korja et al., 2006). The positive εHf(t) values are also consistent with reported values from Svecofennian intrusions (Andersson et al., 2011), however 2 grains with negative values of −8 and −11 are suggestive of mixed Archean and juvenile Svecofennian sources.

The majority of the latest Paleoproterozoic zircons falling within the 1800–1600 Ma age range can be correlated with formation of the Transscandinavian Igneous Belt (TIB) (Larson and Berglund, 1992; Andersson et al., 2004; Gorbatschev, 2004). The TIB is subdivided into several intrusive episodes, of which the earliest (ca. 1.85–1.83 Ga) is limited in its occurrence to the SW Svecofennian border zone (Persson and Wikström, 1993; Andersson and Wikström, 2001; Andersen et al., 2009). The second and most voluminous episode is dated as 1.81–1.75 Ga (Andersson and Wikström, 2001 and reference therein), whilst the third episode occurred ~1.71–1.65 Ma (Brander et al., 2012). The εHf (t) signatures obtained from the Devonian–Lower Carboniferous clastics of Kotel’ny Island are consistent with values reported from the TIB granite (Andersen et al., 2009), with the exception of two grains with negative εHf(t) values of −4 and −6, which could be correlated with values obtained from inherited zircons in rocks from the TIB (Andersen et al., 2009).

The large zircon population falling within the age range 1300–900 Ma can be correlated with known magmatic and metamorphic events associated with the Sveconorwegian-Grenvillian Orogeny (Bingen et al., 2008; Bingen and van Breemen, 1998; McLelland et al., 2010; Pedersen et al., 2009; Rivers, 2008). εHf(t) values of those zircons range from −12 to +11, which are very comparable to εHf(t) values obtained for zircons from Sveconorwegian granitoids (Andersen et al., 2009; Andersen et al., 2007; Pedersen et al., 2009).

The second most abundant population of dated zircons within Devonian–Visean strata is latest Neoproterozoic (ca. 650–550 Ma). Felsic rocks of these ages are not known from the basement of Baltica, however magmatic and metamorphic events falling in the age range

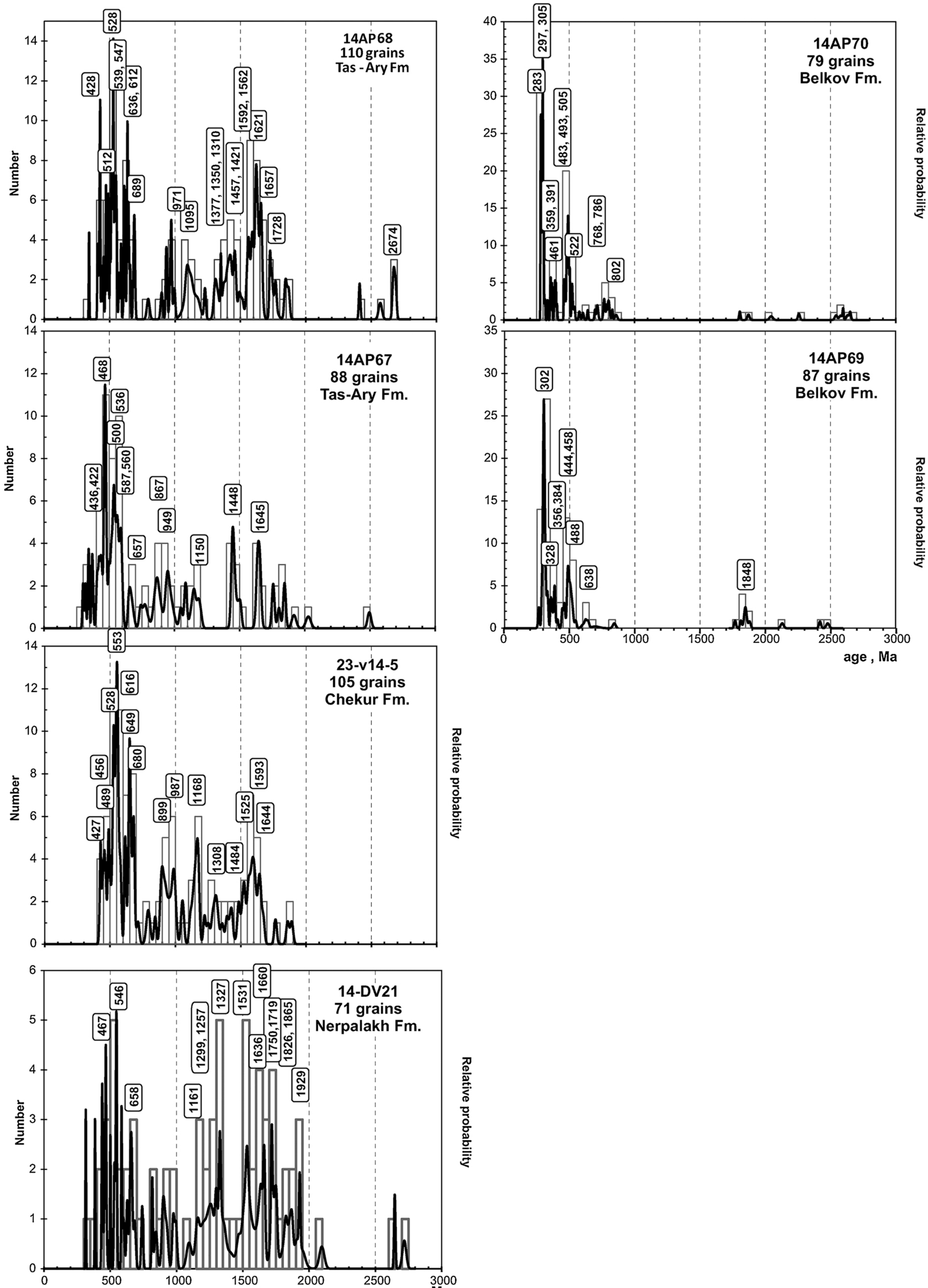

Fig. 6. Probability density diagram and superimposed histogram of U-Pb detrital zircon ages from Devonian – Permian rocks of Area 2.

630–550 Ma have been reported from the Timanian Orogen (Gee et al., 2000, 2006; Kuznetsov et al., 2007), located along the north-eastern margin of Baltica (in modern coordinates). The 650–550 Ma zircon population forms a subvertical mixing array in εHf(t) space and is characteristic of zircon populations associated with continental arcs (Griffin et al., 2002; Kemp et al., 2007). Ordovician–Silurian zircons

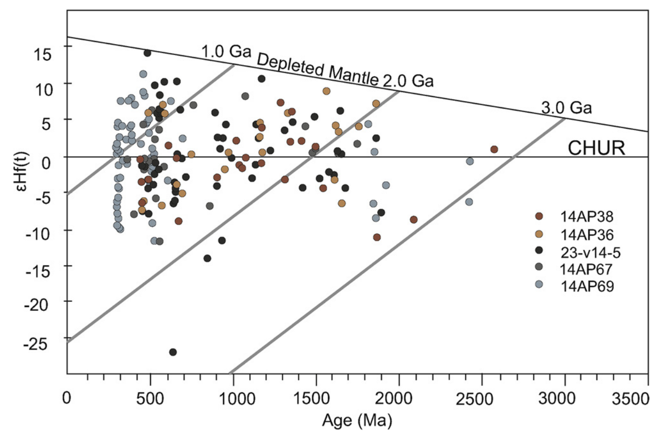

Fig. 7. Initial εHf(t) plotted against age (data from online Attachment 2 in Supplementary materials). Ages are given as $^{206}Pb–^{238}U$ ages if equal to or younger than 1000 Ma, otherwise the $^{207}Pb–^{206}Pb$ ages have been used.

occur in all dated Devonian–Lower Carboniferous samples, suggesting a sediment contribution from the magmatic and metamorphic rocks associated with the Caledonian Orogeny (Gee et al., 2008; Bingen and Solli, 2009). The Early Paleozoic zircons are characterized by εHf(t) values between 0 and −8, indicative of a mixing of juvenile magma with evolved crust, a feature which has been described from the Norwegian Caledonides (Lundmark and Corfu, 2007). Studied sandstones of Devonian–Lower Carboniferous deposits are very mature, with a composition dominated by quartz and lacking unstable grains, favoring the possibility of multiple reworking events from older sedimentary deposits before the grains were finally deposited across the study region. Zircon is a resistant mineral and therefore can undergo several sedimentary reworking events. Similar reworked detrital zircon signatures have been described by Kristoffersen et al. (2014) in Paleozoic rocks of the Oslo Rift, and Hadlari et al. (2015) from the Upper Carboniferous northern Cordillera, as well as revealed by studies of modern river sediments (eg. Morton et al., 2008; Safonova et al., 2010). Therefore, our detrital zircon U–Pb and Lu–Hf data from the Devonian–Lower Carboniferous sandstones of Kotel'ny Island, characterized by a wide variety of ages, suggest that the Paleoproterozoic–Early Neoproterozoic grains in particular are unlikely to have been directly derived from primary magmatic rocks and mainly have been recycled from older strata. However, the presence of younger Paleozoic grains with a striking similarity in both U–Pb ages and Lu–Hf characteristics with the Norwegian Caledonides, along with latest Neoproterozoic grains which perfectly match known magmatic events within the Timanian Orogen, strongly suggest that Kotel'ny Island has an affinity with Baltica during the Devonian–Early Carboniferous, but not the Siberian Craton or Laurentia. A review of available detrital zircon ages from Devonian–Lower Carboniferous strata across the wider Arctic (Fig. 8) reveals a strong similarity between coeval zircon signatures of the NSI, Severnaya Zemlya, Novaya Zemlya and the Canadian Arctic (Franklinian Basin) (Anfinson et al., 2012; Beranek et al., 2013; Ershova et al., 2015b,c; Gasser and Andresen, 2013; Lorenz et al., 2013; Miller et al., 2010; Pease et al., 2015). Consequently, by comparing our results with previous studies (Ershova et al., 2015a,b, 2016a,b; Lorenz et al., 2008; Miller et al., 2010), we suggest that these Arctic regions possibly all formed a single tectonic domain located along the northern margin of Baltica (modern coordinates) during the Late Devonian–Early Carboniferous.

5.2. Uppermost Carboniferous–Lower Permian clastics

Following a significant stratigraphic gap caused by non-deposition or erosion across the study area, the unconformably overlying uppermost Carboniferous–Lower Permian sandstones of the Bel'kov Formation are characterized by very different U–Pb and Lu–Hf detrital zircon signatures, compared to the underlying Devonian–Lower Carboniferous strata. A shift in provenance is also supported by changing sandstone petrography from very mature quartz arenites within the Devonian–Lower Carboniferous clastics below, to lithic arenites along with numerous zircons close to depositional age within the sandstones of the Bel'kov Formation. We therefore conclude that Bel'kov Formation sandstones were derived from primary magmatic rocks during erosion of a coeval orogen. The minor population of Paleoproterozoic and Neoproterozoic grains are characterized by εHf(t) values ranging from +11 to −9, suggesting the mixing of juvenile and evolved crust. εHf(t) values of the Early–Middle Paleozoic population vary from −12 to +11, with the majority having slightly negative or positive values, suggestive of a juvenile magmatic source. By contrast to the underlying clastics, the prevailing positive εHf(t) values are not typical for zircons with affinity to the Scandinavian Caledonides (Lundmark and Corfu, 2007; Kristoffersen et al., 2014). The prevailing Carboniferous–Permian detrital zircon population shows a wide range of εHf(t) values ranging from −10 to +8, suggesting both juvenile and older crust was involved in their genesis and typical for the magmatism associated with continental arcs (Griffin et al., 2002). The voluminous Carboniferous–Permian magmatism widely reported from the Uralian Orogen formed as a result of collision between Baltica, Kazakhstan and Siberia (Puchkov, 1997, 2009). Within the extensive Uralian Orogen, Early Paleozoic magmatic and volcanic rocks are widely distributed and could be a source for zircons of those ages within sandstones of the Bel'kov Formation (Puchkov, 1997, 2009; Degtyarev, 2012 and references therein). Our new detrital zircon data from the uppermost Carboniferous–Lower Permian sandstones are in good agreement with the Permian paleogeographic model of the Arctic proposed by Ershova et al., (2016b,c), which positions the NSI continental block along the Baltican margin with clastics sourced from the western part (present coordinates) of the Uralian Orogen. The data presented here, claiming a Baltican affinity for the NSI, is in good agreement with comparable foraminifera faunas between the NSI and Spitsbergen, Franz Josef Land, Barents Shelf, and Timan-Pechora, which all formed part of Baltica in the Middle–Late Paleozoic (Davydov, 2016). Furthermore, a Baltican affinity is also supported by previous detrital zircon studies on older sediments (Ershova et al., 2016a) and Upper Devonian–Lower Permian sandstones of neighboring Bel'kovsky Island (Ershova et al., 2015c; Pease et al., 2015).

6. Conclusions

Our new U–Pb and Lu–Hf detrital zircon provenance analysis further constrains the provenance of the Devonian–Permian succession of Kotel'ny Island (NSI). The U–Pb age and Lu–Hf signatures of detrital zircons from the Devonian–Visean strata are in good agreement with known ages of magmatic and metamorphic events in Fennoscandia, as well as in the Scandinavian Caledonides, and show clear evidence of a Baltican affinity. However, the very broad distribution of detrital zircon ages and mature composition of the sandstones suggest that these clastics have not been derived directly from primary magmatic rocks, but rather have been reworked from pre-existing sedimentary deposits. There is strong evidence for a significant shift in the provenance area between Visean and Uppermost Carboniferous strata, which is further supported by the immature composition of the uppermost Carboniferous sandstones. The youngest cluster of detrital zircon ages clearly indicates a latest Carboniferous–Early Permian age of the youngest Bel'kov Formation strata, and not Bashkirian as previously suggested. The Bel'kov Formation is characterized by numerous zircons with ages close to the depositional age of the formation, whilst εHf(t) values characteristic of a continental arc environment and an immature composition of the sandstones lead us to conclude that the clastics were derived from the Uralian Orogen. Our new data presented here offers new constraints and considerations for paleogeographic and

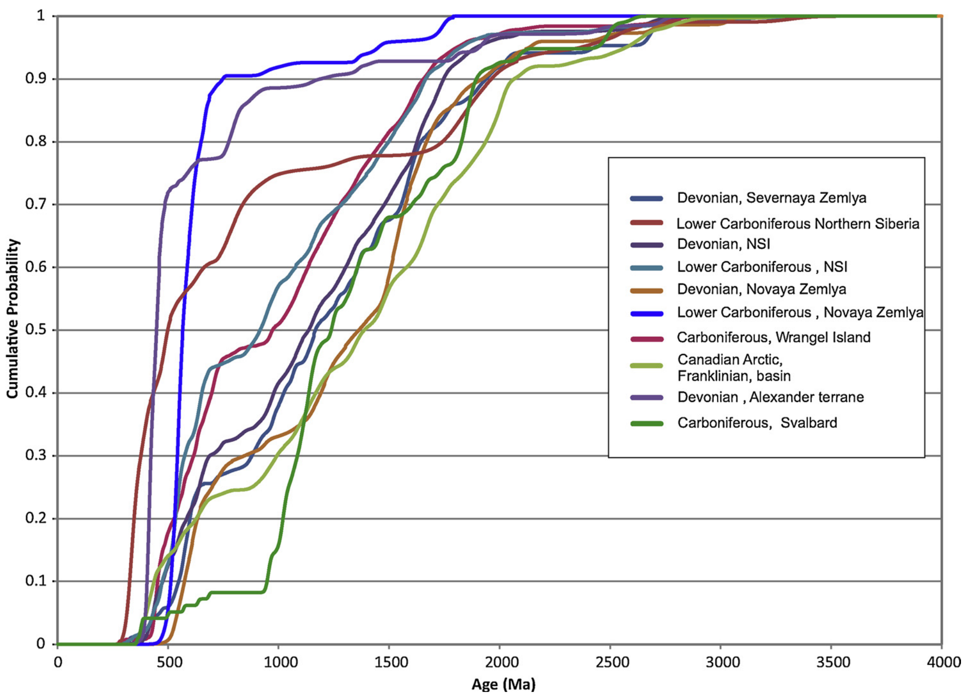

Fig. 8. Cumulative probability diagram U-Pb detrital zircon ages from Northern Siberia (Ershova et al., 2015a), NSI (Ershova et al., 2015b,c; Pease et al., 2015), Novaya Zemlya (Lorenz et al., 2013); Wrangel Island (Miller et al., 2010), Alexander Terrane (Beranek et al., 2013), Canadian Arctic, Franklinian, basin (Anfinson et al., 2012), Svalbard (Gasser and Andresen, 2013); Severnaya Zemlya (Lorenz et al., 2008).

paleotectonic reconstructions of the Arctic realm during the Middle–Late Paleozoic.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jog.2018.02.008.

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